# Comparison of Various Quantification Approaches for Seismic PSA

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## 1. Introduction

A typical PSA (Probabilistic Safety Assessment) quantification is performed in 2 steps as follows:

- Generate minimal cut sets for each sequence, where a success branch is processed using the 'Delete Term Approximation'.
- Evaluate the frequency of each sequence using the REA (rare event approximation) or the MCUB (minimal cut upper bound) method from the obtained cut sets.

In the presence of high-probability events, such as in seismic PSA, the error may become large when using typical PSA quantification approach. Quantification errors in PSA are mainly caused by two reasons [1]:

- Delete Term Approximation: cut sets are obtained by approximating the negate corresponding to the success branch with 'Delete Term Approximation'.
- REA or MCUB: it calculates the approximated probability by REA or MCUB method from the given cut sets
  - REA: error can become very large when CCDP (Conditional Core Damage Probability) is large
  - MCUB: more accurate than the REA. However, it is not recommended for Seismic PSA quantification because it may underestimate when negate is included.

In this article, various PSA quantification approaches that can reduce these errors are examined, and the results of those approaches are compared using two example seismic PSA models.

## 2. Various Approaches for PSA Quantification

Fig. 1 and Table 1 summarize the characteristics of various PSA quantification methods. BDD (Binary Decision Diagram) [2, 10], Monte Carlo [3, 12], Cut Set to BDD [4], PSM (Probability Subtraction Method) [5, 10], and Partial BDD [6, 13] approaches can be used to reduce this quantification error. It should be noted that every approach also has its limitations.

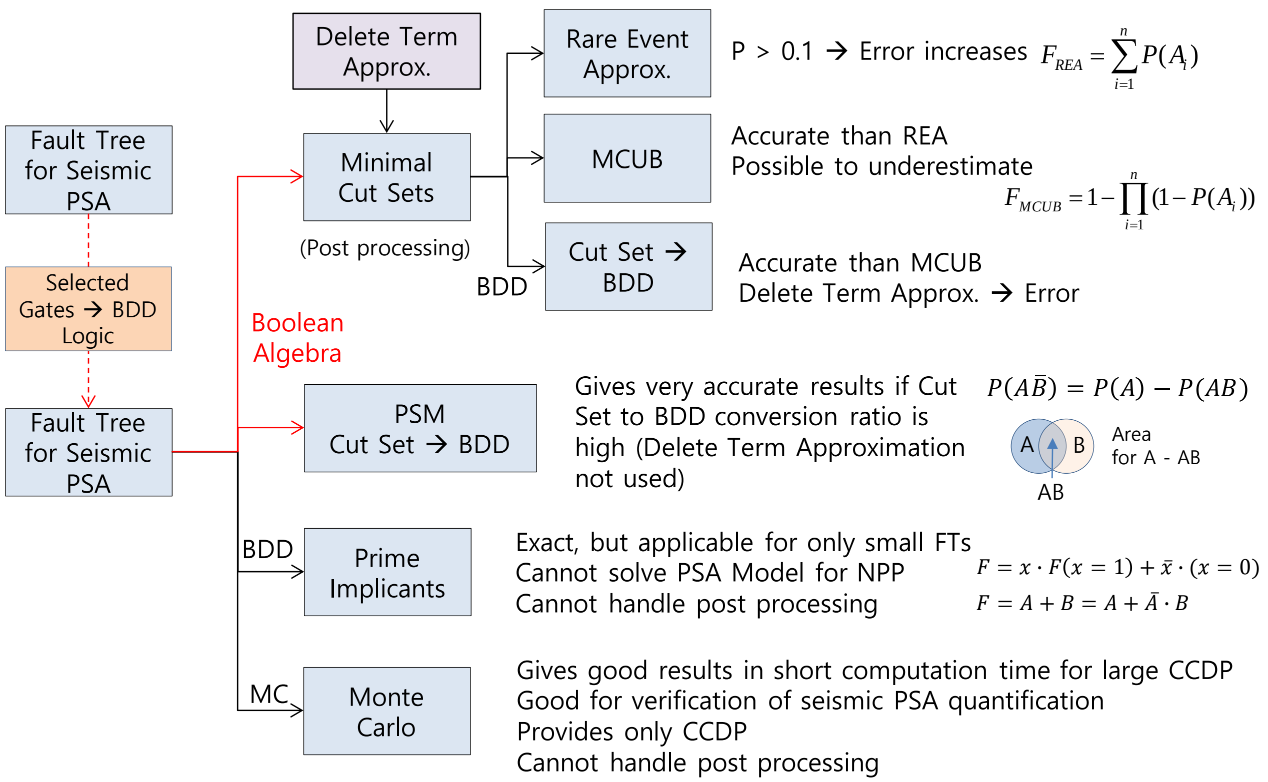


Fig. 1. Various Approaches for PSA Quantification

Table 1. Various Approaches for PSA Quantification

| Approach | Characteristics |
|---|---|
| BDD (SBDD in AIMS-PSA(*)) | • BDD method can calculate the exact probability for a small fault tree.<br>• It cannot solve a large model such as a PSA of nuclear power plant. It cannot also handle post processing (HRA dependency, recovery). |
| Monte Carlo (FTeMC(*)) | • It calculates the top event probability using Monte Carlo approach.<br>• In cases that the CCDP is large, such as in a seismic PSA, it gives fairly accurate values.<br>• It does not provides cut sets which are essential in a PSA, and cannot handle post processing (HRA dependency, recovery). |
| Cut Set to BDD (FTREX, BeEAST(*)) | • It converts cut sets into BDD. This approach can calculate the near exact value for the given cut sets, if 'Cut Set to BDD' conversion ratio is high.<br>• It cannot resolve the error from 'Delete Term Approximation'. |
| PSM (PSM Calculator in AIMS-PSA, FTREX, BeEAST(*)) | • PSM approach handles success branches in an exact way that does not use 'Delete Term Approximation'. It always is used with 'Cut Set to BDD' approach.<br>• 'Cut Set to BDD' conversion ratio is extremely important. It can give very wrong values if 'Cut Set to BDD' conversion ratio is not enough.<br>• We need to be very careful because the result of PSM can oscillate depending on the cut off and 'Cut set to BDD' conversion rate. (It can even produce negative values.) |
| Partial BDD (AIMS-PSA, FTREX, ARES(*)) | • It converts selected gates (such as branches in SIET that includes the key SSCs in a seismic PSA) into BDD logic. It is an extension of Negate-Down approach [7].<br>• It cannot be used for a gate whose size is large.<br>• It can reduce errors greatly even if quantification is done with REA.<br>• If 'Cut Set to BDD' and PSM approaches are combined with partial BDD, the quantification accuracy will be further improved. |

*) PSA quantification software used are FTREX [11], FTeMC [12], SBDD & PSM Calculator in AIMS-PSA [10], BeEAST [4], ARES [13]. ARES is an integrated software for seismic PSA analysis.

## 3. Example Seismic PSA Models for Test

Figure 2 shows a typical Seismic PSA procedure. Following a seismic event, important scenarios are modeled in seismic initiating event tree (SIET), where some scenarios end with direct core damage and some scenarios are transferred to other detailed scenarios (secondary event trees). Since most of SSC (Structure, System and Component) failure important in seismic PSA is modeled in SIET, quantification of the SIET part is very important. Secondary event trees may include failures of the emergency diesel generators, importance pumps, etc., so it is necessary to treat them correctly. However, since the model included in the secondary event trees is large, it is not easy to accurately quantify secondary event trees.

In this article, we use two example seismic PSA models (which are developed for seismic PSA training purpose).

- PP.SPSA : Seismic PSA model for a Pilot Plant
- MP.SPSA : Seismic PSA model for MPAS

These SPSA models were developed by modifying the internal event PSA model as follows:

- It uses a simplified SIET that includes SSCs important for seismic PSA (similar to an existing seismic PSA model where complete dependency is assumed for the redundant SSCs).
- Additionally, seismic failures for emergency diesel generators, major safety system pumps, condensate storage tanks, and safety depressurization system valves are modeled on the secondary event tree (where seismic correlation for redundant SSSs is modeled using the seismic CCF method [8]).

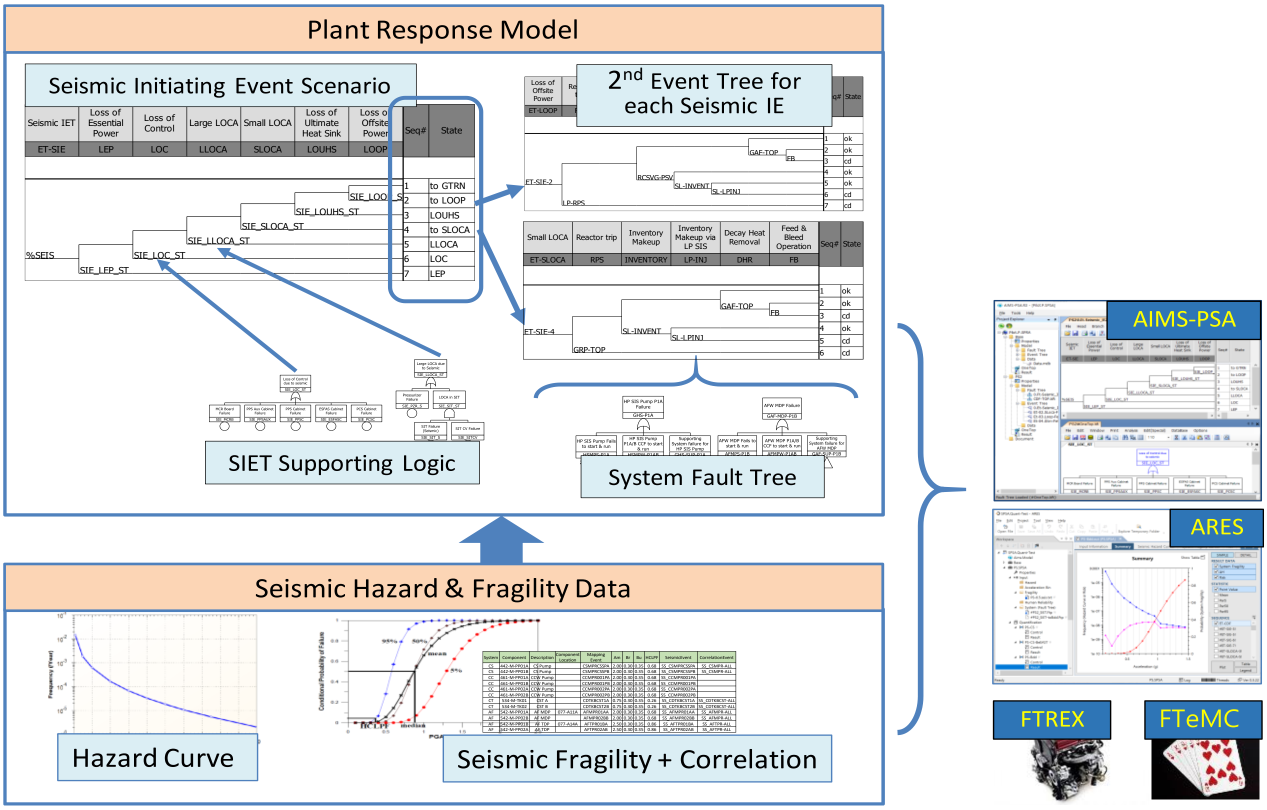


Fig. 2. Typical Seismic PSA Procedure

## 4. Test of Various Approaches for Seismic PSA Quantification

Various PSA quantification approaches are tested for the two seismic PSA models described in session 3.

### *4.1 PP.SPSA Model*

The PP.SPSA model is a seismic PSA model developed for a hypothetical simplified nuclear power plant. The size of the PSA model is quite small, so it can be accurately solved by the BDD method. The results of various quantification approaches are compared with the BDD results. Two types of calculations were performed for this model.

- Total CCDP vs pga (peak ground acceleration)
- Each sequence CCDP for pga=1g

#### *4.1.1 Total CCDP vs pga*

The total CCDP per pga calculated by various approaches are given in Figure 3. These results are summarized below:

- BDD (quantified by the BDD approach) : It provides an exact value at given cutoff
- CS-REA (quantified by typical PSA approach. Cut sets are obtained by ‘Delete Term Approximation’ method and CCDP is calculated by REA) : As pga increases, the error increases rapidly, and even CCDP exceeds 1. It cannot be used for the large pga.
- CS-BeEAST (Cut sets are obtained using the ‘Delete Term Approximation’ and quantified with 'Cut Set to BDD'. BeEAST [4] is a software that converts major cut sets into BDD and quantifies it.) : It is more accurate than CS-REA, and the error becomes about 20% when the pga is large.
- SIET pbdd-CS-REA (It converts SIET with BDD logic, called partial BDD approach in this article. Cut sets are obtained and quantified by the REA.) : It provides a reasonably accurate value. There is about 4% error at a large pga of 1.45g.
- SIET pbdd-CS-BeEAST (It replaces SIET with BDD logic. Cut sets are obtained and quantified with 'Cut Set to BDD'.) : It gives an almost accurate values. There is about 1% error at pga of 1.45g
- PSM (quantified using the PSM and 'Cut Set to BDD') : The PSM method also gives an almost accurate values. There is about 1% error at pga of 1.45g

#### *4.1.2 Sequence CCDP for pga=1g*

Each sequence CCDP is calculated using various approaches for a large pga of 1g. The results are given in Table 2, and summarized as follows:

- BDD (quantified by the BDD approach) : It provides an exact value at given cutoff
- PSM (quantified using the PSM and 'Cut Set to BDD') : When SIET is not converted using BDD, error may be large. If we can lower the cutoff and increase the 'Cut Set to BDD' conversion ratio, it becomes more and more accurate.
- SIET pBdd-PSM (It converts SIET with BDD logic. And it quantifies using the PSM and 'Cut Set to BDD') : It produces an almost accurate values, very close to the BDD results.
- SIET pBdd-CS-REA (It replaces SIET with BDD logic, corresponding to partial BDD approach. Cut sets are obtained and quantified by the REA.) : It provides reasonably accurate values.
- SIET pBdd-CS-BeEAST (It replaces SIET with BDD logic. Cut sets are obtained and quantified with 'Cut Set to BDD'.) : It produces an almost accurate values, very close to the BDD results. Note that it uses 'Delete Term Approximation' in the secondary event tree (which is the cause of the error).

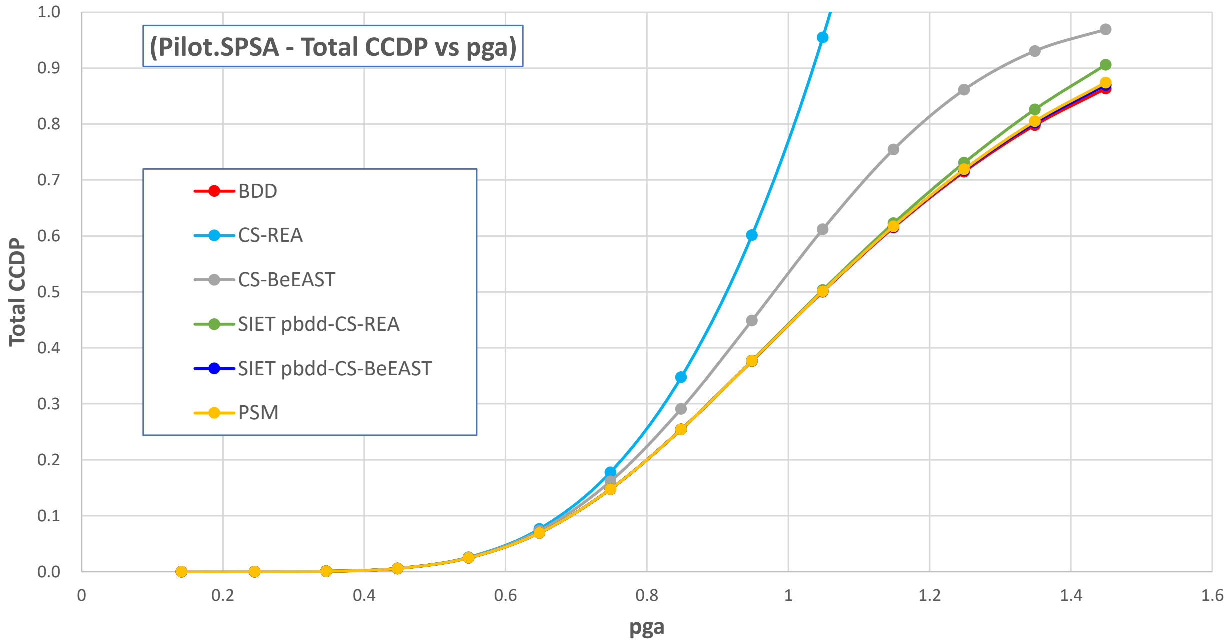


Fig. 3. Total CCDP vs pga for PP.SPSA Model

Table 2. Quantification of each sequence in PP.SPSA Model for pga=1.0g

| Seq | BDD | PSM | | SIET pBdd-PSM | | SIET pBdd-CS-REA | | SIET pBdd-CS-BeEAST | |
|---|---|---|---|---|---|---|---|---|---|
| | CCDP | CCDP | Diff | CCDP | Diff | CCDP | Diff | CCDP | Diff |
| ET-GTRN-3! | 5.067e-8 | 7.149e-8 | 41.1% | 6.179e-8 | 21.9% | 6.521e-8 | 28.7% | 6.179e-8 | 21.9% |
| ET-GTRN-4! | 1.808E-10 | 2.952E-10 | 63.3% | 1.808e-10 | 0.0% | 1.808e-10 | 0.0% | 1.808e-10 | 0.0% |
| ET-LOOP-3! | 1.589e-3 | 7.222e-3 | 354.5% | 1.610e-3 | 1.3% | 1.722e-3 | 8.4% | 1.610e-3 | 1.3% |
| ET-LOOP-6! | 2.669e-6 | 1.257e-5 | 371.1% | 2.777e-6 | 4.0% | 2.961e-6 | 10.9% | 2.777e-6 | 4.0% |
| ET-LOOP-7! | 4.446e-7 | 1.999e-6 | 349.7% | 4.446e-7 | 0.0% | 4.446e-7 | 0.0% | 4.446e-7 | 0.0% |
| ET-SIE-3! | 8.382e-2 | 8.382e-2 | 0.0% | 8.382e-2 | 0.0% | 8.382e-2 | 0.0% | 8.382e-2 | 0.0% |
| ET-SIE-5! | 7.976e-4 | 7.976e-4 | 0.0% | 7.976e-4 | 0.0% | 7.976e-4 | 0.0% | 7.976e-4 | 0.0% |
| ET-SIE-6! | 8.052e-2 | 8.052e-2 | 0.0% | 8.052e-2 | 0.0% | 8.052e-2 | 0.0% | 8.052e-2 | 0.0% |
| ET-SIE-7! | 2.600e-1 | 2.600e-1 | 0.0% | 2.600e-1 | 0.0% | 2.600e-1 | 0.0% | 2.600e-1 | 0.0% |
| ET-SLOCA-3! | 1.034e-3 | 1.580e-3 | 52.8% | 1.043e-3 | 0.9% | 1.128e-3 | 9.1% | 1.097e-3 | 6.1% |
| ET-SLOCA-5! | 1.461e-2 | 2.245e-2 | 53.6% | 1.483e-2 | 1.5% | 1.582e-2 | 8.3% | 1.483e-2 | 1.5% |
| ET-SLOCA-6! | 1.057e-6 | 1.605e-6 | 51.8% | 1.057e-6 | 0.0% | 1.057e-6 | 0.0% | 1.057e-6 | 0.0% |
| Sum | 4.424e-1 | 4.564e-1 | 3.2% | 4.427e-1 | 0.1% | 4.438e-1 | 0.3% | 4.427e-1 | 0.1% |

Note) cutoff=1e-11, C=10000 option (maximum 10,000 cut sets converted into BDD)

### *4.2 MP.SPSA Model*

The MP.SPSA model is a seismic PSA training model based on MPAS [9], an actual PSA model for nuclear power plants. The size of the PSA model is quite large, so it cannot be solved by the BDD approach. For this model, each sequence CCDP is calculated using various approaches for a large pga of 1.225g. Monte Carlo approach is selected as the base case for comparison. C=n option represents the maximum number of cut sets for BDD conversion in ‘Cut Set to BDD’. Results for scenarios with CCDP greater than 1e-6 are shown in Table 3, and summarized as follows:

- FTeMC, n=1e9 (Each sequence CCDP is calculated by a Monte Carlo approach with 1e9 samples. FTeMC is a software to calculate the top event probability using Monte Carlo approach) : Monte Carlo approach provides fairly accurate results for Seismic PSA. We can estimate the error bound of this approach using standard deviation/mean.
- SIET pBdd-PSM, C=10000 (It replaces SIET with BDD logic, and quantifies using the PSM and 'Cut Set to BDD') : It produces fairly accurate values, very close to the FTeMC results.
- PSM, C=3000 (quantified using the PSM and 'Cut Set to BDD') : When SIET is not converted into BDD, the calculation error can be very large and we can get even negative values.
- SIET pBdd-CS-BeEAST, C=10000 (It converts SIET with BDD logic. Cut sets are obtained and quantified with 'Cut Set to BDD'.) : It has similar accuracy to SIET pBdd-PSM approach.
- SIET pBdd-CS-REA (It replaces SIET with BDD logic, corresponding to partial BDD approach. Cut sets are obtained and quantified by the REA.) : There is some error, but it gives a reasonably accurate value.
- CS-BeEAST (Cut sets are obtained using the ‘Delete Term Approximation’ and quantified with 'Cut Set to BDD') : When SIET is not converted into BDD, the calculation error can be large.

Table 3. MP.SPSA Model for pga=1.225g

| Seq | FTeMC n=1e9 | | SIET pBdd-PSM C=10000 | | PSM C=3000 | | SIET pBdd.CS-BeEAST, C=10000 | | SIET pBdd-CS-REA | | CS-BeEAST C=3000 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | CCDP | Std.Dev/ Mean | CCDP | Ratio | CCDP | Ratio | CCDP | Ratio | CCDP | Ratio | CCDP | Ratio |
| SEIS-09! | 4.577e-1 | 0.0001 | 4.577e-1 | 1.00 | 4.577e-1 | 1.00 | 4.577e-1 | 1.00 | 4.572e-1 | 1.00 | 4.577e-1 | 1.00 |
| SEIS-10! | 3.479e-1 | 0.0001 | 3.479e-1 | 1.00 | 3.479e-1 | 1.00 | 3.479e-1 | 1.00 | 3.479e-1 | 1.00 | 3.479e-1 | 1.00 |
| GIE-LOFB-2! | 3.121e-3 | 0.0015 | 3.123e-3 | 1.00 | 3.123e-3 | 1.00 | 3.129e-3 | 1.00 | 3.151e-3 | 1.01 | 1.050e-2 | 3.36 |
| GIE-SLOCA-20! | 1.363e-3 | 0.0012 | 1.378e-3 | 1.01 | -6.537e-4 | -0.48 | 1.378e-3 | 1.01 | 1.558e-3 | 1.14 | 1.628e-2 | 11.95 |
| GIE-LOCCW-2! | 5.824e-4 | 0.0042 | 5.824e-4 | 1.00 | 5.784e-4 | 0.99 | 5.837e-4 | 1.00 | 5.885e-4 | 1.01 | 6.895e-3 | 11.84 |
| GIE-LOFB-3! | 3.206e-4 | 0.0047 | 3.266e-4 | 1.02 | 3.446e-4 | 1.07 | 3.266e-4 | 1.02 | 3.693e-4 | 1.15 | 1.164e-3 | 3.63 |
| GIE-LOCCS-2! | 1.754e-4 | 0.0059 | 1.765e-4 | 1.01 | 1.755e-4 | 1.00 | 1.770e-4 | 1.01 | 1.784e-4 | 1.02 | 2.090e-3 | 11.92 |
| GIE-SLOCA-04! | 1.261e-4 | 0.0089 | 1.323e-4 | 1.05 | -3.051e-4 | -2.42 | 1.578e-4 | 1.25 | 1.834e-4 | 1.45 | 1.888e-3 | 14.97 |
| GIE-LOCCW-4! | 6.007e-5 | 0.0135 | 5.901e-5 | 0.98 | -3.033e-5 | -0.50 | 5.901e-5 | 0.98 | 6.829e-5 | 1.14 | 7.190e-4 | 11.97 |
| SEIS-08! | 3.001e-5 | 0.0147 | 2.987e-5 | 1.00 | 2.987e-5 | 1.00 | 2.987e-5 | 1.00 | 2.987e-5 | 1.00 | 1.002e-4 | 3.34 |
| GIE-LOCCS-3! | 1.818e-5 | 0.0205 | 1.742e-5 | 0.96 | -7.432e-6 | -0.41 | 1.742e-5 | 0.96 | 2.017e-5 | 1.11 | 2.169e-4 | 11.93 |
| GIE-LOOP-19! | 1.263e-5 | 0.0234 | 1.243e-5 | 0.98 | 7.140e-6 | 0.57 | 1.247e-5 | 0.99 | 1.289e-5 | 1.02 | 1.509e-4 | 11.94 |
| GIE-SLOCA-19! | 8.567e-6 | 0.0420 | 8.426e-6 | 0.98 | -7.516e-7 | -0.09 | 9.342e-6 | 1.09 | 1.035e-5 | 1.21 | 1.141e-4 | 13.31 |
| GIE-LOOP-12! | 3.603e-6 | 0.0384 | 3.447e-6 | 0.96 | -2.257e-6 | -0.63 | 3.577e-6 | 0.99 | 3.883e-6 | 1.08 | 4.522e-5 | 12.55 |
| GIE-LOOP-17! | 3.111e-6 | 0.0446 | 2.777e-6 | 0.89 | -8.661e-6 | -2.78 | 3.128e-6 | 1.01 | 3.475e-6 | 1.12 | 4.418e-5 | 14.20 |
| GIE-SLOCA-07! | 2.847e-6 | 0.0512 | 3.212e-6 | 1.13 | -1.760e-5 | -6.18 | 3.221e-6 | 1.13 | 3.717e-6 | 1.31 | 4.183e-5 | 14.69 |
| GIE-LOOP-18! | 1.102e-6 | 0.1131 | 8.881e-7 | 0.81 | 4.311e-8 | 0.04 | 8.909e-7 | 0.81 | 9.959e-7 | 0.90 | 1.219e-5 | 11.06 |
| GIE-LOOP-06! | 1.079e-6 | 0.0968 | 1.004e-6 | 0.93 | -8.772e-6 | -8.13 | 9.099e-7 | 0.84 | 1.089e-6 | 1.01 | 1.562e-5 | 14.47 |

Note) pga=1.225g, cutoff=1e-11, C=10000 option for partial BDD, otherwise C=3000 option (Calculation fails with C=10000)

## 5. Summary

In this article, two example seismic PSA models are constructed, quantification is performed on these models using various approaches, and the results are compared. The characteristics of each quantification approaches are summarized as below:

- The BDD method can provide an exact value. It can solve only small models, so it cannot be used for seismic PSA of nuclear power plants.
- The Monte Carlo method does not provide cut sets, so it cannot be used as a main quantification method. However, it can be used as a useful means of verifying quantification results.
- PSM approach handles success branches in an exact way that does not use 'Delete Term Approximation'. We need to be careful because it can give very wrong values if 'Cut Set to BDD' conversion ratio is not enough.
- Typical PSA quantification approaches (used with REA or MCUB) produce large errors for a seismic PSA. 'Cut Set to BDD' or PSM approach can reduce error but it has limitations.
- The partial BDD approach, where the SIET is converted into BDD logic, can provides reasonably accurate results, even if it is used with REA. Combined use of the partial BDD approach with 'Cut Set to BDD' or PSM can provides more accurate results.
- When using Negate, the MCUB method is known to have the potential to underestimate results.

The method recommended in this article is to convert SIET (that includes the key SSCs in seismic event) into BDD logic and use the typical PSA quantification method for the rest. With this partial BDD approach, we can obtain reasonably accurate quantification values. If 'Cut Set to BDD' and PSM approaches are combined here, the quantification accuracy will be further improved.

Approaches to perform accurate quantification for large fault tree models from secondary event trees remain to be resolved. If research on this issue is carried out, seismic PSA quantification can be processed more accurately.

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